

PATENT SPECIFICATION

(11) 1257 779

DRAWINGS ATTACHED

- (21) Application No. 58002/67 (22) Filed 21 Dec. 1967
 (21) Application No. 59028/67 (22) Filed 29 Dec. 1967
 (23) Complete Specification filed 19 Dec. 1968
 (45) Complete Specification published 22 Dec. 1971
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G3R 40 7R 9A 9B 9J X

- (72) Inventors EDWARD STUART ECCLES and
 DAVID JAMES MOORE



(54) OPTIMIZING CONTROL SYSTEM

(71) We, ROLLS-ROYCE LIMITED a British Company of Moor Lane, Derby, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:

This invention relates to an optimizing control system.

According to this invention there is provided a system for varying an input of a manufacturing or power plant automatically to drive an output of the plant to a maximum or minimum value, comprising a digital computer adapted to act on said input and respond to said output and programmed to perform iteratively the operations of converting a pseudo-random binary sequence into a perturbation signal where-in one of the two types of digit of the sequence produces a ramp signal component successive ones of which are of opposite slope and the other type of digit produces signal components of uniform level connecting the successive ramp components, applying the perturbation signal to the plant input, reading the consequential perturbations of the plant output, correlating the perturbation signal and the consequential perturbations to determine the slope of the input/output relationship.

SPECIFICATION NO 1257779

By a direction given under Section 17 (1) of the Patents Act 1949 this application proceeded in the name of THE SECRETARY OF STATE FOR DEFENCE, London.

R 68695/1

THE PATENT OFFICE

jet tube 18 and a burner 14, a turbine 16 adapted to drive the compressor, a burner is connected to a fuel supply controlled by a valve 22 which is operable by a signal 1. The nozzle 20 is connected to an actuator 24 for varying the area of the nozzle. The actuator 24 is operated by a signal 2. The signals 1, 2 are hereinafter also referred to as "parameters".

Variation of the parameters 1, 2 causes changes in the output X of the engine as measured by a thrust sensor 26. The variation of X is shown by the characteristic in Fig. 2 where it is defined by the area 12X. The maximum or optimum thrust obtainable by variation of the parameters 1, 2 is denoted by a point X max. Assuming the output X is at a point X₀, then movement of the output along a line Z_r is necessary to attain X max. Z_r has components Z₁ and Z₂ in the directions of the axes of the parameters 1 and 2 respectively.

The engine is controlled by a digital computer 28 which is adapted to vary the parameters 1, 2 to maintain X at X max. To this end the computer is programmed to:—

- a) impart perturbation signals B₁, B₂ to the respective signals 1, 2. These perturbations are added to the signals 1, 2 at summing junctions 30, 32.

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According to this invention there is provided a system for varying an input of a manufacturing or power plant automatically to drive an output of the plant to a maximum or minimum value, comprising a digital computer adapted to act on said input and respond to said output and programmed to perform iteratively the operations of converting a pseudo-random binary sequence into a perturbation signal where-
10 in one of the two types of digit of the sequence produces a ramp signal component successive ones of which are of opposite slope and the other type of digit produces signal components of uniform level connecting the successive ramp components, applying the perturbation signal to the plant input, reading the consequential perturbations of the plant output, correlating the perturbation signal and the consequential perturbations to determine the slope of the input/output relationship, generating a correction signal which is a function of said slope relationship and indicative of the sense in which the input has to be varied to drive the output to said maximum or minimum value, and applying the correction signal to the input.

20 An example of a control system according to this invention will now be described with reference to the accompanying drawings wherein:—

Fig. 1 is a system diagram.

Fig. 2 is a characteristic of certain signals occurring in the system.

Fig. 3 shows certain aspects of Fig. 1 in greater detail.

25 Fig. 4 is a diagram of pulses occurring in certain signals of the system.

Fig. 1 shows a plant in the form of a gas turbine engine 10 comprising in flow-series a compressor 12, a burner 14, a turbine 16 adapted to drive the compressor, a jet tube 18 and a variable area exhaust nozzle 20 supported by the jet tube. The burner is connected to a fuel supply controlled by a valve 22 which is operable by a signal 1. The nozzle 20 is connected to an actuator 24 for varying the area of the
30 nozzle. The actuator 24 is operated by a signal 2. The signals 1, 2 are hereinafter also referred to as "parameters".

Variation of the parameters 1, 2 causes changes in the output X of the engine as measured by a thrust sensor 26. The variation of X is shown by the characteristic in Fig. 2 where it is defined by the area 12X. The maximum or optimum thrust obtainable by variation of the parameters 1, 2 is denoted by a point X max. Assuming the output X is at a point X₀, then movement of the output along a line Z_r is necessary to attain X max. Z_r has components Z₁ and Z₂ in the directions of the axes of the parameters 1 and 2 respectively.

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1.

SPECIFICATION AMENDED - SEE ATTACHED SLIP

- b) receive the signal X which now contains perturbations occurring in consequence of the signals B1, B2.
- c) analyse the signal X with respect to the signals B1, B2 to determine the effect of these signals on X.
- 5 d) generate correction signals Z1, Z2 for the varying the respective parameters 1, 2 in the sense causing change of X towards X max. 5

To ensure discrimination between the signals B1, B2 for the purpose of said analysis, the latter signals are based on a group of pseudo-random binary numbers (PRBN). A PRBN is a sequence of signals which have the property of zero correlation with all shifted versions of itself. This is best explained with reference to Fig. 3 which shows details of the computer 28. A shift register 30 contains the binary sequence 1110100 and is adapted to output the sequences A1, A2...An, where n equals the number of digits of each sequence and also equals the total number of different sequences it is possible to have in the group. The sequences A1 to An are PRBN as can be shown by correlating any two sequences. 10 15

Correlation between two sequences is defined as forming their correlation coefficient which, in turn, is defined as the process of summing the products of the signals of the corresponding digits of the two numbers. In this context the sign of a digit is taken to be +1 if the digit is binary 1, and -1 if the digit is binary 0. Applying this to the two sequences A1, A2 in Fig. 3, it will be seen that the products 35 of the signs form the sum -1. The same sum, i.e. the same correlation coefficient, is produced by correlation any two of the sequences B1 to Bn. But if the correlation is made between any of the sequences and itself, i.e. between identical sequences, then the correlation coefficient is +7. This shows that it is possible to recognize any one of the sequences A1 to An uniquely from all the other sequences. The recognition process will be understood by adding the corresponding digits of the respective sequences. This gives a sequence Ax referred to as the collective noise. If the sequence Ax is correlated with any of the sequences A1 to A7, say the sequence A1, it will be found that the correlation products form a sequence Ax identical with A1. This means that it is possible to have access to any one of the sequences which constitute the sequence Ax. It will be noted that, in the present example, the correlation coefficient for two identical sequences is +7. This is so because the sequences chosen each have one more "1" than "0". If the number of "0"s and "1"s in the sequence is made equal, as by removing one "1", then the correlation coefficient for two identical sequences is +6. The corresponding correlation coefficient for unequal sequences would, in the present example, be zero. Thus, if for any reason the PRBN has an odd "0" or "1" and thereby does not correlate to zero, the zero correlation can be ensured by neglecting the odd "0" or "1". The significance of this will become apparent later herein. 20 25 30 35

40 For the purpose of forming the correction signals Z1, Z2 the computer is programmed to perform the following calculation:— 40

$$(1) \quad S_j = \frac{1}{(n-1)|B_{jo}|} \left\{ \sum_{i=0}^{n-1} [\text{Sgn} (B_{ji}) \times \bar{X}_i] - \text{Sgn} (B_{jp}) \times \bar{X}_p \right\}$$

$$(2) \quad C_j = \frac{-4}{(n+1)|B_{jo}|^2} \left\{ \sum_{i=0}^{n-1} [\text{Sgn} (A_j (i + \frac{1}{2})) \times \bar{X} (i + \frac{1}{2})] - \text{Sgn} (A_j (q + \frac{1}{2})) \times \bar{X} (q + \frac{1}{2}) \right\}$$

$$(3) \quad Z_j = \frac{S_j}{C_j}$$

wherein:—

j=the number (1, 2, 3, . . . n) of the parameter.

Z_j=the correction signal for parameter j.

5 S_j=the slope of parameter j.

C_j=the curvature (i.e. rate of change of slope) of parameter j.

A_j=the PRBN sequence selected for the control of parameter j.

B_j=the signal A_j in ramp form, for the purpose of perturbation of parameter j, and as varying to either side of a zero mean.

10 n=the total number of digits in the PRBN sequence; also the total number of parameters j which can be controlled by sequences having n digits.

i=the number 0, 1, 2, . . . n) of any one of the digits.

X̄=the output signal of the plant as perturbed by the signal B_j and as varying to either side of a zero mean.

15 P=a value of i such that B_{ji} is positive.

q=a value of i such that A_j (i + ½) is negative.

The above formulae can easily be written in any well-known programming language and be read into the computer to constitute a programme therein. The data

on which the programme has to act is constituted by the signals A_j, B_j and X̄.

20 The significance of the various steps of the above formulae and their interaction with the engine will now be described in detail.

The cycle of the register 33 is initiated by a start signal 34 which determines what is referred to as the sampling period of the system. The signal 34 also initiates a timing signal 36 (Fig. 4) which determines the time period of the digits i of the PRBN sequences. The sequences A₁, A₂ are equivalent to square waves and it is arranged that the time period of each digit i of the sequence extends over two pulses of the signal 36.

25 The computer programme may be regarded as comprising four sections 38, 40, 42 and 44 (Fig. 3) concerned respectively with generating the values B_j, S_j, C_j and Z_j.

30 In section 38 the original A₁ is converted into the signal B₁ which is a ramp signal based on a non-return-to-zero response to the signal A₁. This means that the signal A₁ is used to generate ramps 46 successive ones of which are of opposite slope so that the signal does not have any sharp rise or fall. To make it possible for the signal B₁ to be an identifiable representation of the signal A₁ only one of the two types of digit, "1" or "0", are converted into the ramps 46, the other digits remaining in the signal B₁ as uniform levels 47. Inasmuch as it is a property of the pseudo-random binary number that the two types of digit occur respectively an even and an odd number of times, the digits chosen for conversion into ramps are those occurring an even number of times so that the signal B₁ starts and ends at the same level and no change of level is necessary when the signal is repeated. As mentioned, the signal B₁ is connected to the summing junction 30 to impart to the signal 1 a perturbation, and it will be clear that this perturbation corresponds to the ramps 46, i.e. the signal 1 is caused to rise and fall in accordance with the ramps 46. The mean level of the signal B₁ is denoted 0 and corresponds to the level which the signal 1 would have in the absence of the perturbations. The forming of an arithmetical series in the computer in order to generate the ramp signal, and the establishment of the mean level of the signal, will be well understood in the programming art.

45 It will be recalled that the signal A₁ has one more "1" than "0". This is done to ensure that the signal B₁ can join the corresponding signal B₁ in the next sampling period without a vertical step. But this odd "1" will be eliminated later in the programme.

50 One advantage of using a non-return-to-zero ramp signal for the perturbation of the signal 1 is that the engine is capable of responding to such a signal with reasonably good fidelity. If the signal were a square wave instead of a ramp, then the engine would have difficulty in responding accurately to the sharp rises and falls of such a square wave; also the engine would be subjected to undue wear.

55 Similarly to the signal B₁, the signal B₂ is a non-return-to-zero ramp signal based on the signal A₂ and connected to corresponding perturb the signal 2.

60 The combined effect of the signals B₁, B₂ on the engine causes in the output X

there a perturbation \bar{X} as shown in Fig. 4. Fig. 4 also shows the component signal X_1 which represents the effect which the signal B_1 would have if applied alone, and a corresponding component signal \bar{X}_2 which shows the individual effect of the signal

B_2 . The signals \bar{X}_1 , \bar{X}_2 do not exist as such when the parameters 1, 2 are perturbed simultaneously. However they are shown because the object of the correlation is to

recognize the slope and curvature of these signal \bar{X}_1 , \bar{X}_2 .

In section 40 of the programme there is determined the slope S_1 of the signal \bar{X}_1 by correlation of the signals B_1 , \bar{X} in accordance with formula (1). The slope S_2 of the signal \bar{X}_2 is determined similarly. Taking B_1 into the formula, as an example

it will be seen that the expression $\text{Sgn}(B_{1i}) \times \bar{X}_i$ gives the product of the sign of the signal B_1 at each of the seven digits i from 0 to 6. The expression $\text{Sgn}(B_{1p}) \times \bar{X}_p$ is subtracted in order to eliminate the odd "1". The summation of these products gives the correlation coefficient. Dividing the summation by $n-1$ determines the mean

change of \bar{X} , (which is the same as the mean change of X) and the further division

by the modulus of B_1 when $i=0$ gives the slope S_1 . As regards the signal \bar{X} , it will be understood how to form the mean of the perturbations of the signal X and present

the signal \bar{X} as positive or negative departures from that mean. This is done in a section 39 (Fig. 3) of the programme by adding the highest and lowest values of the excursions of X during the sampling period, and dividing the result by 2 to form a mean. The mean is then subtracted, in each digit i of the sequence, from the value

of X_i to produce the sequence \bar{X} . It will be appreciated that the shape of \bar{X} is in fact the same as the shape of X but its mean is zero.

It will also be seen that the signal X is equivalent to the signal A_x in the general example of correlation given earlier herein above, and that the correlation between B_1 ,

\bar{X} reads on to the component \bar{X}_1 of the signal \bar{X} just as in the general example the sequence A_1 read on to the sequence A_{1x} . However, whereas in the general example the individual sequences to be added, to form the sequence A_x , each remained unchanged, i.e. each had a gain of 1, in the application of the sequences A_1 , A_2 to the engine, these latter sequences will have gains other than 1 as is apparent from the

signal \bar{X} as shown in Fig. 4. The correlation properties, however, of the signal are not substantially affected by such gains.

In formula (2) C_j is determined in section 42 of the programme by correlation of A_j and \bar{X} . The expression $\text{Sgn}(A_{j(i+\frac{1}{2})}) \times \bar{X}(i+\frac{1}{2})$ gives the correlation products

and their summation gives the correlation coefficient. The term $\text{Sgn} A_{j(q+\frac{1}{2})} \times \bar{X}(q+\frac{1}{2})$ is subtracted to eliminate an odd "0". Division by $(n+1)/2$ gives the mean

excursion of the signal \bar{X} at the midpoints of the digits i , that is at $i+\frac{1}{2}$, which excursion is an index of curvature. Multiplication by $-2/B_{j0}^2$ gives an approximation to first derivative of slope, i.e. to curvature.

In formula (3), in section 44 of the programme, the slope is divided by curvature to establish the correction signals Z_1 , Z_2 which are output to the summing junctions 30, 32 to drive the parameters 1, 2 to the point X max. The fact that the slope is divided by the curvature means that where the slope is zero, the correction signal will be zero regardless of any inaccuracies in curvature. It can be shown that if the surface $12X$ is based on a quadratic equation then the transition from the point X_0 to the point X max. can be made by a single correlation routine. Otherwise two or more such routines are necessary to attain X max., and it will be understood of course that the computer operates continually to carry out these routines to restrain the engine in the X max. condition.

Any number of parameters up to $n-1$ may be used subject however to any possible interaction between the parameters in the plant.

The main advantages of the invention arise from the fact that PRBN are used in combination with a two-level non-square perturbation signal. A two-level signal is one which rises and falls continuously between a highest and a lowest point and does not halt for a significant length of time at any one intermediate level. The ramp signal is an example of this, and such signals are of course easy to produce and process. A non-square wave signal is one which does not have the sharp steps which characterise the square wave form but which is in the form of a ramp, a sign wave or any other form which is capable of identifying a digit of the PRBN without sharp steps. Such waves are referred to as non-square waves or as waves having a finite slope. The significance of this requirement is that a square step makes it difficult to determine

the slope of the signal \bar{X} when that slope is at or near zero. To illustrate this point,

Fig. 4 includes a signal $\bar{X}1a$ which is the variation of the signal $\bar{X}1$ when the parameter 1 is close to a maximum point $X1$ max. on the surface $12X$. As in the case

of the signals $\bar{X}1$, $\bar{X}2$ and \bar{X} , so also the signal $\bar{X}1a$ is defined in relation to a zero mean to make possible the establishment of the positive and negative values of the signal for the purpose of slope correlation. If the signal $B1$ had been a square wave

instead of a non-square wave, then the signal $\bar{X}1a$ would have consisted of sharp spikes and this would have made it difficult or impossible to obtain a significant measurement of the value of the signal at the top of the spike and, as stated, such measurement is necessary for forming the mean value which establishes the zero line. Thus the invention makes it possible to attain good accuracy at the very point of the signal X , i.e. X max., at which the system is required to maintain the output of the engine. It is emphasized that this accuracy is obtained from a single two level signal such as a ramp signal and that there is no need to go more complex signals, for example signals having three levels to obtain flattening at the top of said spikes, to obtain accuracy.

Further, the present invention makes it possible to obtain accurate measurement of curvature by the use of a simple two-level signal such as a ramp signal. It

will be clear that if the signal Bj had been a square wave, the signals $\bar{X}1$, $\bar{X}2$, \bar{X} would have substantially vertical sides 54. This would make it impossible to form

the value of \bar{X} at $i+\frac{1}{2}$ in formula (2) unless employing a more complicated signal pattern, e.g. a three-level signal.

The computer is provided with switch means (not shown) for being connected or disconnected to the summing junctions 30, 32 and the sensor 26. When the computer is not in operation the plant is controlled, e.g. manually, by signals 50, 52 to the summing junctions 30, 32.

WHAT WE CLAIM IS:—

1. System for varying an input of a manufacturing or power plant automatically to drive an output of the plant to a maximum or minimum value, comprising a digital computer adapted to act on said input and respond to said output and programmed to perform iteratively the operations of converting a psuedo-random binary sequence into a perturbation signal wherein one of the two types of digit of the sequence produces a ramp signal component successive ones of which are of opposite slope and the other type of digit produces signal components of the successive uniform level connecting ramp components, applying the perturbation signal to the plant input, reading the consequential perturbations of the plant output, correlating the perturbation signal and the consequential perturbations to determine the slope of the input/output relationship, generating a correction signal which is a function of said slope relationship and indicative of the sense in which the input has to be varied to drive the output to said maximum or minimum value, and applying the correction signal to the input.

2. System according to Claim 1 wherein the computer is programmed so that it is a type of digit occurring an even number of times in the sequence which is converted into said ramp components.

3. System according to Claim 1 or Claim 2 wherein for the purpose of determining said slope the computer is programmed in respect of each digit of the sequence

to correlate the sign of the excursion which the perturbation signal makes relative to a mean value thereof at the start of the period defining the duration of the ramp component or uniform level with the excursion which said consequential output makes at a corresponding point in time.

5 4. System according to any one of the preceding claims, wherein the computer is programmed to correlate the binary sequence with said consequential perturbations to determine the curvature of the input/output relationship, and generate said correction signal as a function of said slope and curvature. 5

10 5. System according to Claim 4 wherein the computer is programmed to correlate the sign of each digit of the sequence (the two types of digit being taken respectively as positive and negative) with the excursion which said consequential output makes in respect of a mean value thereof at a point intermediate between the start and finish of the period defining the duration of the ramp components or the uniform levels. 10

15 6. System according to any one of the preceding claims wherein the two types of digit of the sequence occur respectively n and $n+1$ number of times, and wherein the computer is programmed to eliminate one digit from the $n+1$ digits as far as the correlation process is concerned. 15

20 7. System for varying an input of a manufacturing or power plant automatically to drive an output thereof to a maximum or minimum value substantially as described herein with reference to the accompanying drawings. 20

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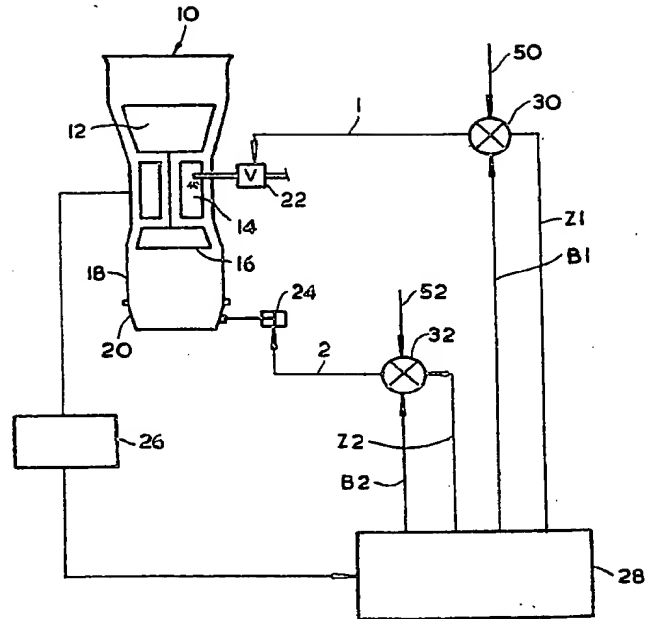


FIG. 1.

COMPLETE SPECIFICATION

*This drawing is a reproduction of
the Original on a reduced scale*

Sheet 2

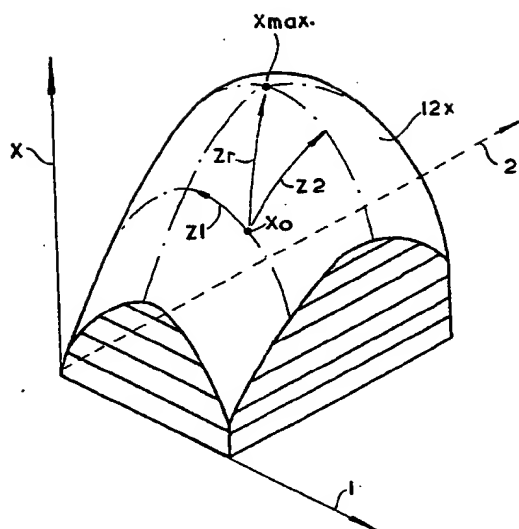


FIG. 2.

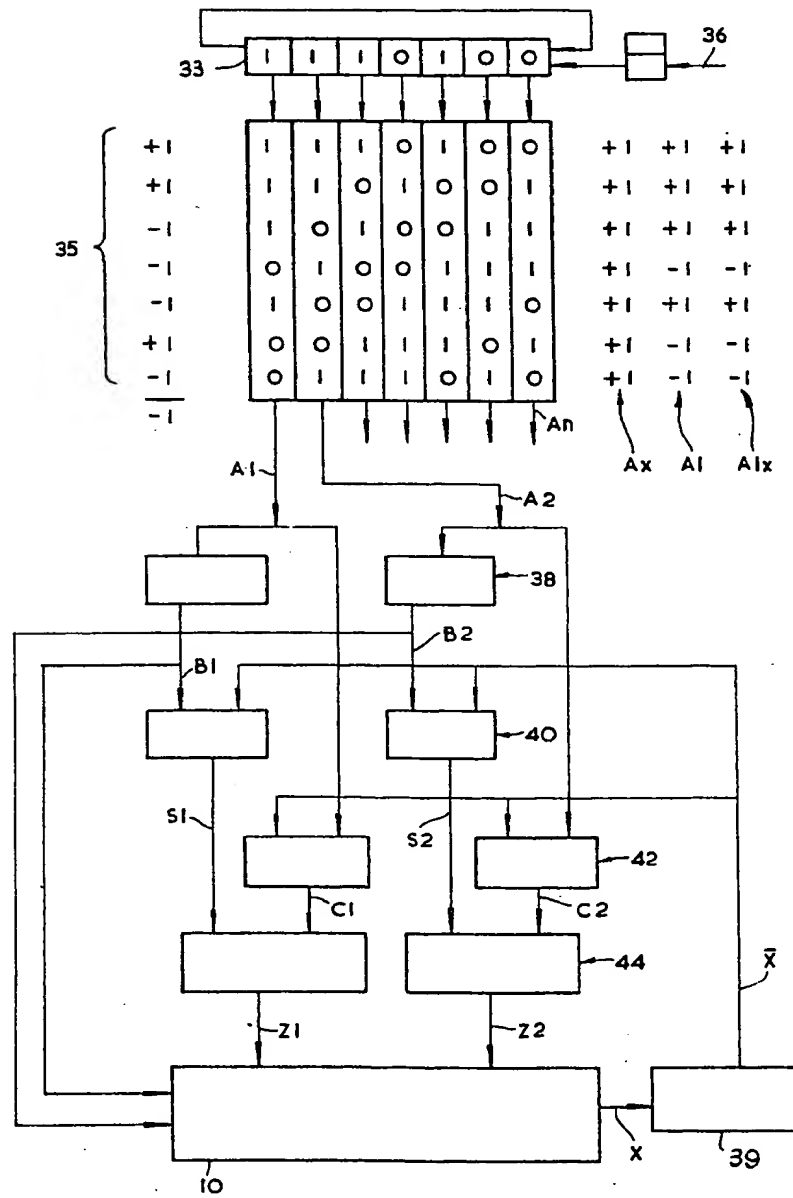


FIG. 3.

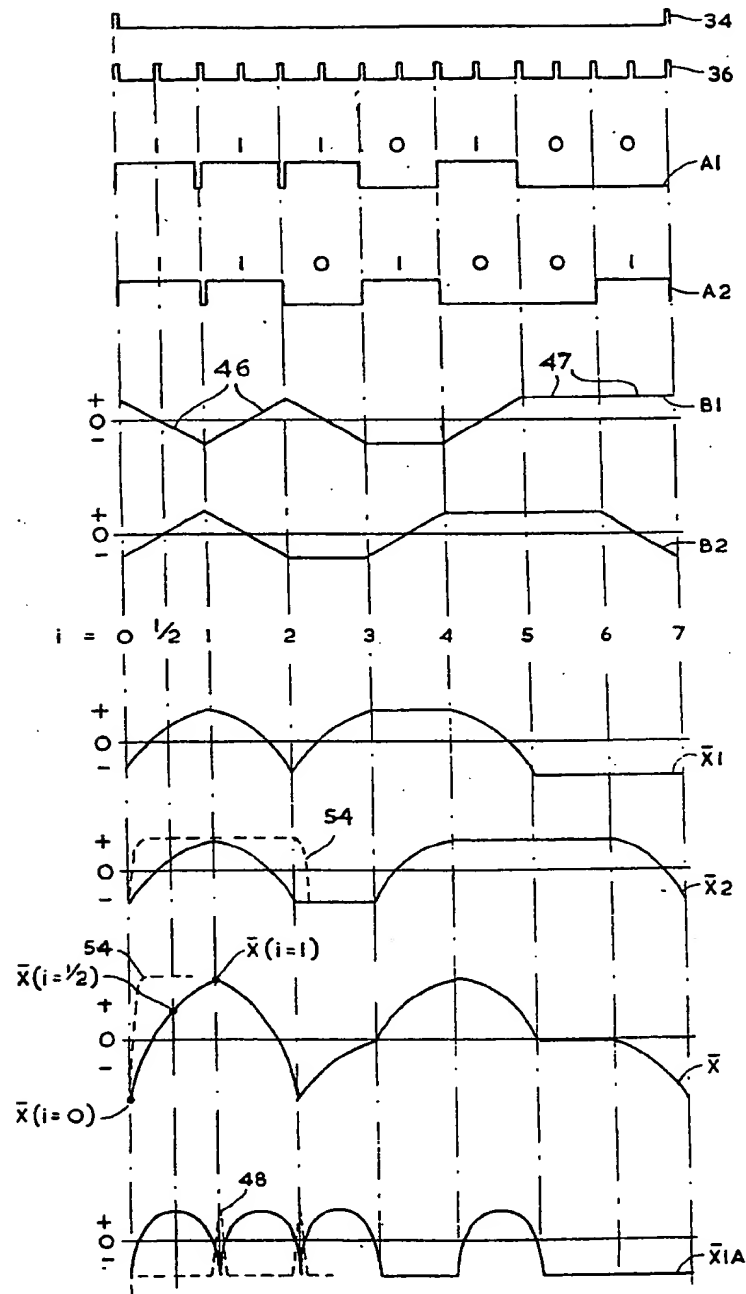


FIG. 4.